Antenna Optimization Study on Stryker Vehicle Using FDTD Technique

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Abstract
The purpose of this antenna optimization study is to perform antenna placement optimization for the Blue Force Tracking (BFT), Iridium, and International Maritime Satellite (INMARSAT) antennas on the proposed Mounted Battle Command On The Move (MBCOTM) Stryker system. The MBCOTM Stryker system uses the Stryker Command Vehicle (CV) as its baseline. Engineering analysis of the Stryker CV points out a number of challenges with the antenna integration. First and foremost, the BFT, INMARSAT, and Iridium share the same operational frequency bands. This presents a large potential for co-site interference on the Stryker platform. A second challenge is the degradation of antenna performance when located in close proximity to large metallic obstructions such as the weapon, hatch covers, ammo boxes and other antennas. Without proper antenna placement, these obstructions can have a significant impact on the antenna gain (Fig1,2).

To optimize these communication systems on the MBCOTM Stryker system, this study will evaluate the current (baseline) antenna placements for both co-site interference and antenna gain. This study will also develop and evaluate an alternate configuration with the objective of increased antenna gain pattern performance and decreased co-site interference. This study uses Computational Electromagnetic Modeling (CEM), specifically the Finite Difference Time Domain (FDTD) method, to model and simulate effects of antenna placement on the Stryker. The traditional design method for antenna placement was based solely on engineering experience and empirical test data. CEM provides many additional measurable statistics to evaluate antenna placements. This study integrates CEM analysis and statistics into the traditional design method to optimize antenna performance.

I. Introduction

The scope of this study is to perform analysis and placement optimization for the BFT, Iridium, and INMARSAT antennas. Initial antenna locations were determined based on the location of other antennas, the operational requirements of the soldiers (provided by PM-BCOTM), mechanical considerations (existing hull pass-thru locations given that an armored hull is not easily penetrable) and the operational requirements of the communication system. Initial antenna locations were evaluated based on the simulated pattern performance and co-site analysis (Fig1) and used as a baseline for alternate antenna placements.

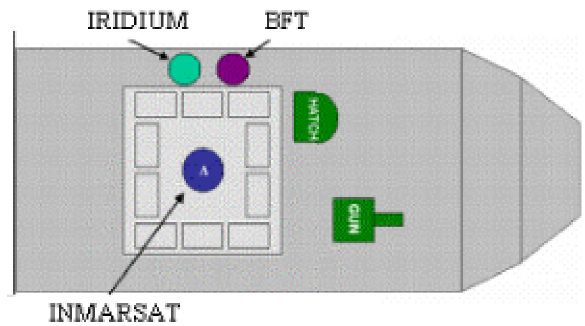

Fig1. Baseline (Initial) antenna locations.

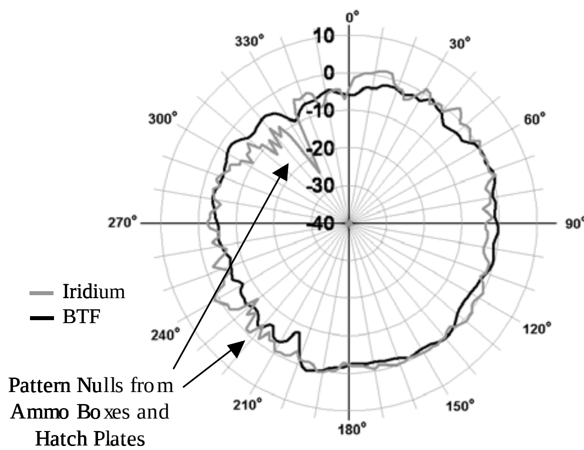

Fig2. Azimuth gain patterns for Iridium and BFT at baseline locations.

Nine antennas are currently mounted on the Stryker, namely, one HF (High Frequency), three SINCGARS (SINgle-Channel Ground and Airborne Radio System), one NTDR (Near Term Digital Radio), one EPLRS (Enhanced Position Location Reporting System), two GPS (Global Positioning System), and a UHF SOTM (Ultra High Frequency Satcom On The Move). The BFT, INMARSAT and Iridium antenna locations were limited to areas of the platform where antennas were not currently located.

Operational requirements for the ammunition stowage area, the hatch area, and the area in front of the weapon

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(Fig1), limited the real estate for antenna placement. Antenna placement in proximity of the ammunition boxes was limited, due to the 6" height of the boxes. The hatch, when opened, serves as an obstruction for any antenna in close proximity. Lastly, the area in front of the weapon was limited for line of fire reasons.

The INMARSAT system is currently the primary data link for the MBCOTM Stryker system. This is a critical system for the vehicle and was considered the highest priority for the antenna placement study. The current system design uses the electromechanically steered (EMS Cyclone) directional antenna with +17dBiC gain and high transmit power. The antenna can be steered 360 degrees in azimuth and 90^{o} in elevation, enabling the system to communicate at any chosen look angle above the horizon. The INMARSAT antenna operates over the 1.525 – 1.661GHz band and is used in the 1.54 to 1.545GHz band for Army applications[1]. Fig3 shows the validated INMARSAT antenna model pattern results.

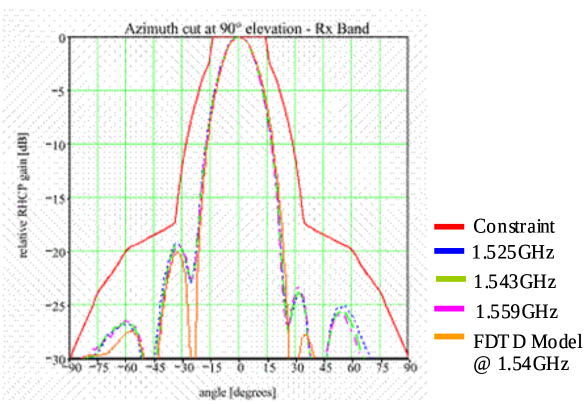
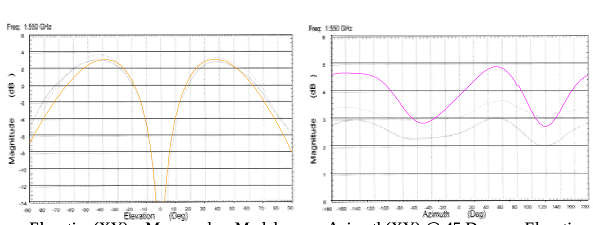


Fig3. INMARSAT validated antenna model pattern results.

Another critical system on the Stryker variant is the BFT system. BFT operation is considered mission essential and operates in the 1.626 to 1.646GHz transmit band and 1.530 – 1.544GHz receive band[2]. Fig4 shows the validated BFT antenna model pattern results.



Elevation(XY) – Measured vs Model

Azimuth(XY) @ 45 Degrees Elevation – Measured vs Model

Fig4. Blue Force Tracking validated antenna model pattern results.

The Iridium Phone antenna, made by Aeroantenna, operates in the 1.616 – 1.626GHz band. This antenna is used in the 1.616 to 1.626GHz band for Army applications[3]. This system is a new addition to the Stryker communication architecture. The Iridium system is used as a back-up voice communications radio and is considered a lower priority than the BFT and INMARSAT systems. The validated Iridium antenna model pattern results are illustrated in Fig5.

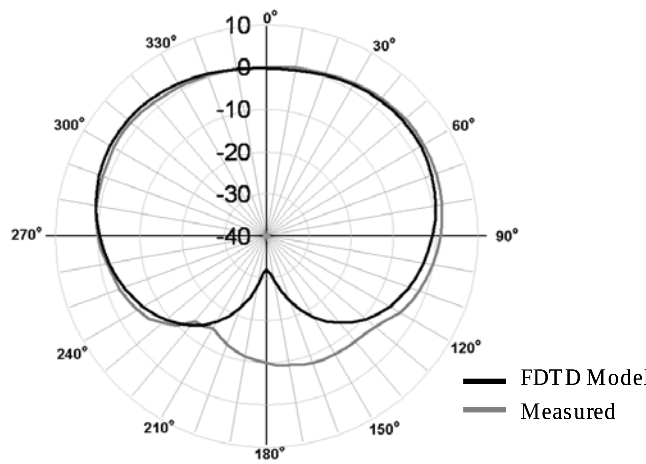


Fig5. Iridium validated antenna model pattern results.

BFT, INMARSAT and Iridium systems use a satellite relay architecture for end-to-end connectivity [1,2,3]. Thus, the antenna placement must provide an unobstructed view of the sky in all directions. Omni-directional antennas used for satellite communication however, are typically limited in performance in the azimuth direction. The BFT antenna is optimized for communication above 20^{o} (3dB point). The BFT yields an azimuth gain of –4.5 dBiC and much better performance with 0.75dBiC at 20^{o} elevation. The Iridium system performance is optimized for lower angle performance. This antenna is optimized for communication directly at the horizon. However, propagation effects typically limit use below 8.5^{o} elevation [5]. While the antennas must face the sky, structures below the 20^{o}/ 8.5^{o} look angle will not affect antenna pattern performance. This notional concept also has disadvantages. For example, if the platform was to tilt, (as will certainly happen in the real world) the nearby structures initially below the 20^{o} or 8.5^{o} mark may now be in an obstructing position. Throughout this study it is assumed that the platform is parallel to the ground.

Another factor considered in the antenna placement is the dependence of antennas on the ground plane. The Iridium antenna is a broad side propagating quadrafile antenna fed through a small internal ground plane[3].

This produces an omni-directional gain pattern independent of an external ground plane. This antenna is typically mounted on a 0.36-meter composite mast, which further shows that it is a ground plane independent design. The INMARSAT is a phased array electro-mechanically steered antenna[1]. The array uses patch elements with a reflective back plane. This antenna system is inherently ground plane independent. Lastly, the BFT antenna is a layered circular patch, which is also a ground plane independent design[2].

II. Finite Difference Time Domain (FDTD)

The Finite Difference Time Domain (FDTD) technique [4] was used to model the platform, obstructions, and the antennas. FDTD is based on Maxwell's curl equations.

$$\frac{\partial H}{\partial t} = -\frac{1}{\mu}\nabla \times E - \frac{\rho'}{\mu}H \qquad (1)$$

$$\frac{\partial E}{\partial t} = -\frac{1}{\varepsilon}\nabla \times H - \frac{\sigma}{\varepsilon}E \qquad (2)$$

Yee's Algorithm is used to calculate Maxwell's curl equations based on finite difference approximations of space derivatives and time derivatives. Two key parameters that are important for accuracy and stability when using the FDTD technique are the cell size (α) and the time step (Δt) [4].

$$\alpha \le \frac{\lambda}{10} \qquad (3)$$

$$\Delta t \le \frac{1}{\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}}} \qquad (4)$$

The maximum cell size must be less than or equal to $1/10^{th}$ (some cases $1/20^{th}$) the wavelength of the highest operational frequency. For the Iridium, BFT, and INMARSAT frequencies, this relates to a maximum cell size of 1 cm cube edges. However, in order to model the small dimensions of the antennas, a cell of a finer resolution (2mm cube edge) was required. Since the antennas must be modeled with a maximum cell size of 2mm and the Stryker is a large vehicle, it would be beyond the available memory and time resources of the project to simulate a Stryker within the 2mm cell size. For this reason, each antenna was built in a 2mm sub grid within the 1 cm Stryker main grid. For pattern analysis, a single sub grid was used for the stimulated antenna. For co-site analysis, a second sub grid was added to include the victim antenna.

The maximum time step (Δt) is based on the grid size ($\Delta x, \Delta y, \Delta z$), and is quite large for the Stryker platform. The time step is determined from the Courant condition, which is solved by determining the time that a given point of a plane wave propagates from a given FDTD cell to only its directly neighboring cells[4].

III. INMARSAT Antenna Gain Pattern Analysis

For our study, the INMARSAT system is the highest priority and the most difficult antenna to move on the platform (due to size and limited mounting options). Hence, it was determined that choosing an optimal INMARSAT location was the first step in optimizing all antenna locations. From PM-BCOTM, there were three possible locations (A,B,C) for the INMARSAT Antenna (Fig6). Additionally, three physically large static objects were seen as potential RF obstructions – metallic ammunition boxes stowed on the top center of the Stryker (6" in height), the hatch on the driver side front of the vehicle (typically open), and the vehicle weapon.

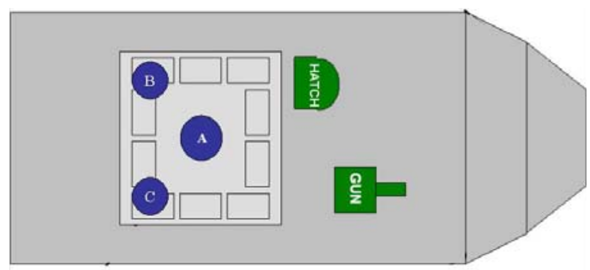


Fig6. Possible locations for INMARSAT antenna.

To optimize the INMARSAT antenna performance, the characteristics of the antenna in close proximity to the obstructions were simulated. This was done by placing the antenna and obstruction, into an experimental solution space (ESS). The antenna was tested within the ESS at the various distances (associated with the vehicle antenna placement) and angles (associated with the orientation of the vehicle obstruction) to determine the antenna pattern/obstruction relationship. Since there were no other geometries in the ESS, degradation in the antenna pattern performance was attributed directly to the obstruction.

To limit the time needed to analyze all the data that would be obtained from such an experiment, individual frequencies were chosen across the band of the antenna and pattern information for the INMARSAT was collected only when pointed directly at the obstruction. It was assumed that when the antenna was pointed directly at the obstruction the pattern performance would be at its worst case. Antenna locations were then compared upon this data.

Fig7 shows the effects of the Hatch obstruction on the azimuth pattern of the INMARSAT antenna when placed at three different distances within the ESS. Fig7 shows a 5dB decrease in gain in the direction of the hatch obstruction between the three antenna locations.

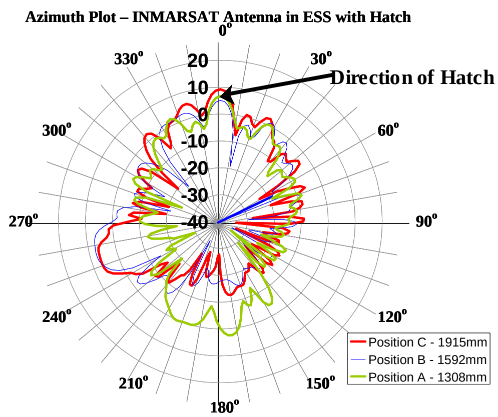


Fig7. Hatch Effects on INMARSAT Pattern at Three Potential Antenna Placement Locations.

Fig7 also shows that the gain does not increase linearly with distance (away from the obstruction), as one might expect. If fact, position A, which is closer to the obstruction, has better gain in the direction of the obstruction than position B. This is one particular non-intuitive relationship that could not be determined without extensive field-testing. However, this type of relationship has previously been investigated with the use of FDTD modeling and is typically the result of destructive or constructive reflections. Since the gain pattern differences between the 3 locations did not vary significantly, it was recommended to keep the INMARSAT antenna at its original position, namely location A.

IV. INMARSAT Cosite Interference

Cosite interference is defined as degradation to a communication system due to interference from a co-located system. Effects of cosite interference vary greatly. Cosite interference effects typically degrade communication range. However, in extreme cases cosite interference can saturate the victim receiver into a nonlinear state and damage receiver components. The three systems being integrated into the Stryker (BFT, INMARSAT, and Iridium) share the same operational frequency bands, which creates a cosite interference challenge. Since an optimal location for the INMARSAT Antenna has already been determined (see section III of this report), the cosite interference was investigated between the INMARSAT and various Iridium locations, and also between the INMARSAT and various BFT locations.

A known cosite interference problem exists between the INMARSAT and Iridium systems. These systems require a minimum of 50ft. of separation to avoid cosite interference as defined in the Iridium documentation[5]. Interference to the BFT system from the Iridium and INMARSAT systems has not been experimentally quantified. It was recommended to PM-BCOTM that testing be conducted to quantify any potential interference challenges. As an initial estimate of the allowable interference to the BFT system, it was assumed that the BFT front-end was similar in design to the Iridium system. As a result, restraints similar to the Iridium (50ft minimum separation) were put on the BFT antenna location.

Based on these parameters, initial antenna locations were chosen to increase isolation (over the current locations) through distance and/or the use of an obstruction as an isolating mechanism.

Pattern analysis of the antenna/obstruction experiments also gave valuable information on the isolation achieved behind a structure as well as the direction of the reflected energy. Results from the hatch open obstruction (Fig8) showed a large amount of energy at the angle of reflection, allowing us to avoid antenna placements in that region.

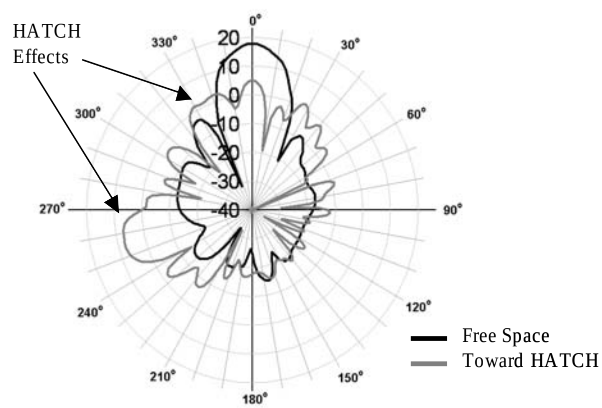


Fig8. Hatch Open Effects on INMARSAT Pattern.

The Iridium documentation [5] states that the isolation must be at a level similar to that seen at 50 ft. of separation to avoid co-site interference between the INMARSAT and Iridium systems[5]. Converting this distance to path loss using the free space path loss equation (5)[6] we are able to determine the isolation between the INMARSAT and Iridium antennas.

$$P_L = [\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}] \quad (5)$$

where G_t is the gain of the Transmit antenna (INMARSAT for our case), G_r is the gain of the Receive antenna (Victim Iridium for our case), λ is the wavelength based on operation frequency (1.540GHz for our case), and d is the separation distance in meters (15.24 meters or 50 ft. for our case).

In order to use Equation (5), we are assuming that our system is operating in 'far-field' conditions. This will allow us to use G_r and G_t values that were obtained via free-space simulations for the INMARSAT and Iridium systems. The conditional equations for 'far-field'[7] are given in equations (6a), (6b), and (6c).

$$d_f = \frac{2D^2}{\lambda} \qquad (6a)$$

$$d_f >> D \qquad (6b)$$

$$d_f >> \lambda \qquad (6c)$$

where d_f is the minimal distance for 'far-field' in meters; λ is the wavelength based on operation frequency (1.540GHz for our case); and D is the largest electrically radiating dimension of either antenna (whichever is larger).

For the INMARSAT and Iridium systems, the following variable values were used:

$G_{t\ dB}$ = +17 dB; $G_{r\ dB}$ = 0 dB; λ = 0.195 m;
d = 50 feet = 15.24 m; D = 5 inches = 0.127 m

Hence,

$$P_L = -10\log[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}]$$
$$= -G_{tdB} - G_{rdB} - 20\log(\lambda) + 20\log(4\pi) + 20\log(d)$$
$$= 42.84 dB$$

From the path loss calculation, we see that there has to be 42.8 dB of isolation between the INMARSAT and Iridium antennas. In free space environment, this can be achieved with 50 feet of separation between the two antennas. It is obvious that we do not have 50 feet on top of the Stryker, so there needs to be a way to lower the separation distance between the two antennas and still achieve 42.8 dB of isolation. This is accomplished by placing an obstruction between the two antennas. The weapon is the largest and most stationary obstruction on top of the Stryker. Using the weapon as an obstruction, there is a 14-dB drop in the gain of the INMARSAT antenna (Fig9). From Fig9, there is a reduction in Gain for G_{tdB} from 17dB (black trace) down to 3dB (gray trace). Therefore the gain for G_{tdB} in the direction of the weapon obstruction is 3 dB.

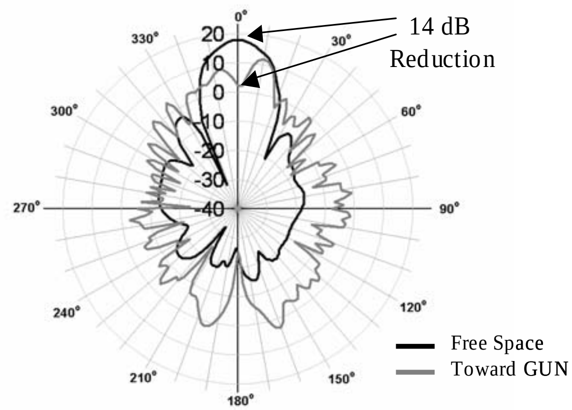


Fig9. Weapon Effects on INMARSAT Pattern (14 dB Reduction).

Next, we compute the new separation distance using the path loss equation and the 14 dB net drop.

$$P_L = 42.84 dB$$
$$= -(3) - 20\log(\lambda) + 20\log(4\pi) + 20\log(d) \Rightarrow$$
$$d = 3.04m \approx 10 ft.$$

With the weapon as an obstruction between the two antennas, we can achieve the 42.8 dB of isolation at a minimum separation of 6 feet between the antennas. This separation is a feasible solution for the Stryker platform.

Cosite analysis of the BFT system followed a similar procedure. The assumption that the BFT required similar isolation parameters as the Iridium became the threshold to which cosite was measured.

The initial BFT antenna placement was located on the top of the Stryker platform approximately 3.4 ft. from the INMARSAT antenna. This antenna placement is extremely close to the INMARSAT. In anticipation of possible cosite interference an initial precaution was taken to use a metallic box to isolate the BFT and INMARSAT antennas. The box was retrofit to the existing antenna mount and comes to the same height of the BFT antenna. This allows the antenna to communicate above the horizon while blocking a direct line of sight path to the INMARSAT antenna.

The initial antenna placement with the metallic box provided 25.7 dB of isolation between the BFT and INMARSAT systems.

The final antenna placement was chosen to increase antenna isolation. This placement shown in Fig10, increases the distance between the BFT and INMARSAT and additionally uses the Stryker hull as an obstruction to increase isolation. The final antenna placement has 35.4 dB of isolation between the INMARSAT and BFT systems.

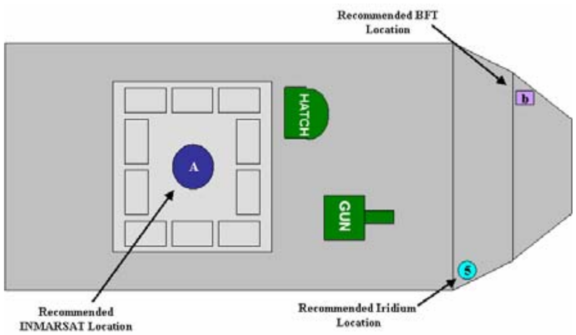


Fig10. Recommended locations for the BFT, Iridium, and INMARSAT antennas.

The final antenna placement for the BFT was not able to achieve the 42.8dB of isolation that was used as our threshold measurement. However, an additional filter was recommended for use with the Iridium system that has been successful in reducing cosite effects [5]. Similar filtering techniques for the BFT along with the proper antenna placement will significantly reduce the co-site interference on the Stryker platform.

It was also recommended to PM-BCOTM to conduct electromagnetic compatibility testing on the BFT and INMARSAT systems prior to antenna installation.

V. Iridium and BFT Gain Patterns and Cosite

The locations for the BFT and Iridium antennas (Fig10) were determined based on reducing cosite interference from the INMARSAT system. It is now important to characterize the gain patterns of the Iridium and BFT antennas in their new locations, as well as the cosite interference between the BFT and Iridium systems.

In the locations of Fig10, the BFT antenna gain pattern was not significantly affected by the platform obstructions (weapon, hatch, ammo boxes) in the area of interest. The look-angle affected by the obstructions was significantly lower than the 20^{o} (β) desired look-angle.

Analysis of the Iridium system showed substantial gain pattern degradation due to its close proximity to the weapon. However, the use of the weapon as an isolating obstruction from the INMARSAT system was a necessary performance trade off.

Finally, the isolation between the Iridium and BFT systems in their new locations was simulated (via FDTD) to be 35 dB. Initial field testing from PM-BCOTM stated that a minimum of 6-ft. free-space separation was required between two BFT systems. Based on our assumption of similar front-end design of the Iridium system, we assumed a 6ft. minimal separation between BFT and Iridium systems. The calculated on-platform isolation of 35 dB corresponds to approximately 7½-ft of free-space separation. This insured that cosite interference between the BFT and Iridium systems would not be a problem.

VI. Conclusions

Our recommendation is to place the Iridium, BFT, and INMARSAT Antennas as shown in Fig10. This will reduce the co-site interference between the three systems, while keeping gain pattern degradation and affected look-angles by obstructions to a minimum. Additional RF filtering is recommended for both the BFT and Iridium to combat INMARSAT cosite interference

The optimized antenna configuration of Fig10 adheres to the recommendations for 35 dB of isolation (7-8ft separation) between Iridium and BFT antennas, 38 dB of isolation (as close to the recommended 42 dB isolation that could be obtained) between INMARSAT and Iridium antennas, and 34 dB of isolation (7.3 ft separation) between INMARSAT and BFT antennas. Additionally, the antennas are generally removed from large obstructions (weapon, hatch, ammo boxes) and are located in areas on the Stryker where it is feasible to mount an antenna.

An important result in our isolation analysis showed that simply moving the antenna to a remote location on the platform was not sufficient to obtain the required isolation. New and innovative techniques (such as using the weapon obstruction to increase isolation) could generate a feasible antenna solution on the Stryker variant.

While it is not practical to make exact dimensioned placement recommendations due to a large number of platform constraints (i.e. pre-cut antenna mounting holes), this study has provided antenna location recommendations based on general guidelines that will enhance communications and reduce co-site interference on the Stryker platform.

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***[1], [2], and [3] contain proprietary and non-disclosure data and results. Please contact the AA Branch, CERDEC, Ft. Monmouth, NJ for access to these documents.*
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